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HIGGS BOSON PRODUCTION AND SCATTERING PROCESSES BEYOND THE PERTURBATION THEORY

(İSAAC GROUP ACADEMY Collaboration)

PROTVINO 2025

REPORT STRUCTURE:

MOTIVATION AND INTRODUCTION 2.

Understanding the mechanism that generates the masses of elementary particles through electroweak symmetry breaking (SB) has been one of the fundamental efforts in particle physics for several decades. It is well known that the description of the theory in the Standard Model (SM), in particular, electroweak interactions, begins with a doublet of complex scalar fields, and after SB, three of four initial material scalar fields are extinguished by gauge fields, and only one neutral scalar Higgs field remains.

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The SM Higgs boson mass $M_H = \sqrt{2\lambda}\,\upsilon$ is determined by the self-coupling parameter λ in the SM scalar potential $V(\Phi) = m^2 \Phi^+ \Phi + \lambda\left(\Phi^+ \Phi\right)^2$ with the expectation value $\upsilon \approx 246\,GeV$ of the Higgs field.

Therefore, the quartic coupling λ is a free parameter in the SM. This means that there is no a priori prediction for the mass of the Higgs particle, and at the same time the sign of the mass parameter is negative for electroweak SB and there is no clear understanding of what determines this sign.

The experimentally determined Higgs boson mass, $M_H \approx 125\,GeV$, means that $\lambda \approx 0.13$ and $|m| \approx 88.4\,GeV$:

- Navas S. et al. Status of Higgs Boson Physics (Particle Data Group) // Phys. Rev. – 2024 – *D* 110 – 3, 030001.
- T.-P. Cheng, L.-F. Li. Gauge theory of elementary particle physics – Oxford. Clarendon Press, 1984. – 536 P.

The theoretical expectation of the upper bound on the **4.**
Higgs particle mass $< 350\,GeV$ (with allowance for small values of the interaction constant according to perturbation theory (PT))

Navas S. et al. Status of Higgs Boson Physics (Particle Data Group) // Phys. Rev. – 2024 – *D* 110 – 3, 030001.

has been experimentally confirmed by the ATLAS and the CMS:

- Aad G. et al. (ATLAS Collaboration) Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC // Phys. Lett. – 2012. – V. B716. – P. 1–29.
- Chatrchyan S. et al. (CMS collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, // Phys. Lett. – 2012. – V B716. – P. 30–61.

collaborations at the Large Hadron Collider (LHC), so discovery of this resonance with a mass of approximately $125\,GeV$ certainly has far-reaching implications.

The fundamental particles couplings to the Higgs particles are set by their masses. This new type of interaction is very weak for light particles (e.g., and quarks, and electrons), but strong for heavy particles (e.g., - and -gauge bosons and -quarks). That is, the SM Higgs boson couplings to fundamental fermions are linearly proportional to the fermion masses, whereas the couplings to gauge bosons and as well as the Higgs boson self coupling are proportional to the square of the gauge boson masses and square of the Higgs boson masses: **5.**

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$$L_{\text{int}} = - g_{Hf\bar{f}} \bar{f} f H + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{24} H^4 +$$

$$\delta_G V_\mu V^\mu \left(g_{HGG} H + \frac{g_{HHGG}}{2} H^2 \right),$$

where $g_{HF\bar{F}} \equiv y_F = m_F / \upsilon$, $g_{HGG} = 2 m_G^2 / \upsilon$, $g_{HHGG} = 2 m_G^2 / \upsilon^2$

$g_{HHH} = 3 m_H^2 / \upsilon$, $g_{HHHH} = 3 m_H^2 / \upsilon^2$, $G = W^{\pm}$ or Z^0, $\delta_W = 1$, $\delta_{Z^0} = 1/$

Workman et al.(Particle Data Group). Status of Higgs Boson Physics// Prog. Theor. Exp. Phys. – 2022, 083C 01.

In particular, the coupling of the Higgs boson with gluons

Workman et al.(Particle Data Group). Status of Higgs Boson Physics// Prog. Theor. Exp. Phys. – 2022, 083C 01.

Shifman M.A., Vainshtein A.I., Voloshin M.B. and Zakharov V.I. Low-Energy Theorems for Higgs Boson Couplings to Photons // Sov. J. Nucl. Phys. – 1979 – V. 30. – 711 [Yad. Fiz. – 1979 – V. 30. – P. 1368 – 1378]. Ellis J. R., Gaillard M. K and Nanopoulos D. V. A phenomenological profile of the Higgs boson //, Nucl. Phys. – 1976. – V. B106. – P. 292–340

is induced in the leading order by a one-loop process in which Higgs boson is coupled to a virtual pair of quarks, while the contribution of other lighter quarks is smaller. And the photons coupling to Higgs boson is also generated via loops, although in this case the one-loop graph with a virtual -pair provides the dominant Contribution, and it is interfering destructively with the smaller contribution W^+W^- involving a vitual - pair.

$t\bar{t}$

The Higgs boson interacts with very heavy particles **8.**
(preferably -or -bosons, or -quark and then with lepton or b-quark), it is not related directly to massless photons or gluons. This creates a theoretical opportunity to investigate the following processes of forming Higgs particles: an electron-positron pair annihilation into an excited -boson with its further decay into a - boson and a Higgs boson; model production of a -boson through a -quarks triangular diagram, which formed as a result of interaction of gluons ;

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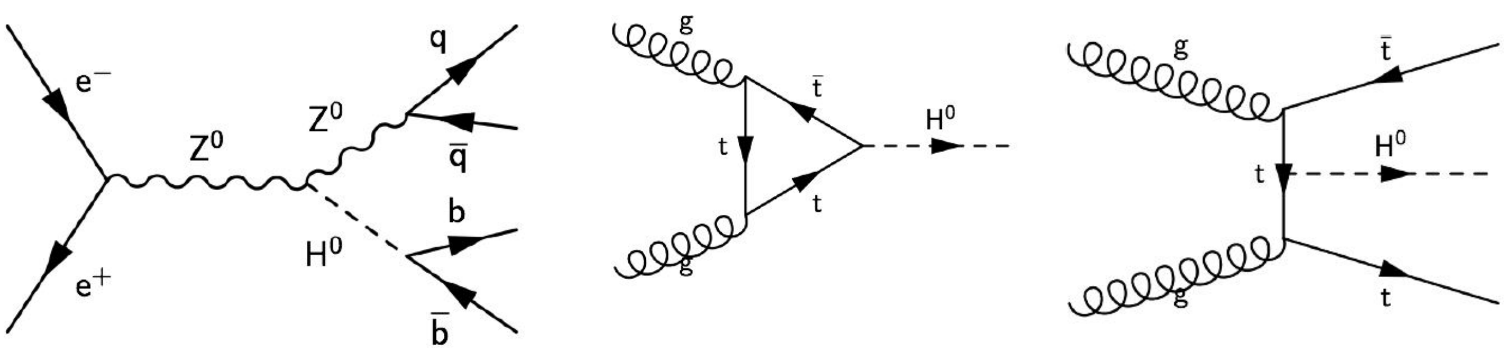
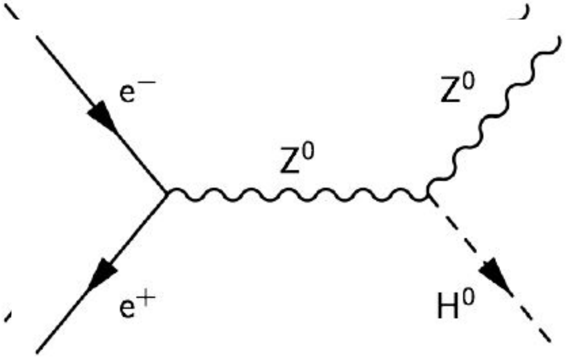
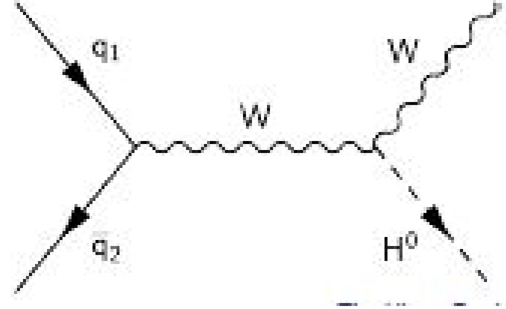


the process of gluon scattering with -quark exchange;**9.** and production of the -boson through channels of annihilation and scattering of two quarks (q_1 and q_2) with exchange by the virtual W - or Z - bosons, with with further formation of H - and (or)-bosons on the pair of quarks (q_3 and q_4) beyond PT. As is well known, the Higgs bosons taking part in the coll-sions can also be expected in the $p\bar{p}$ collisions (for example, in the process ee^+) with futher decay $ee^+ ® Z^* ® ZH$. It is believed that scattering of particles in the deeply inelastic range of momentum change $H ® 2g$ occurs via the exchange by the entire trajectory of particles.





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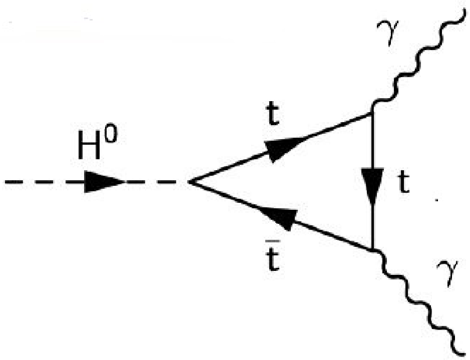


The scattering amplitudes of particles are mainly calculated by the PT method. It is well known that beyond PT, nontrivial results are obtained within the framework of the gauge field theory. It is also well known that summation of the ladder-type diagrams always leads to the integral BS equations for the scattering amplitude 11.

Arbuzov B. A., Logunov A. A., Tavkhelidze A. N. and Faustov R. N. Regge poles and the Bethe-Salpeter equation // Dokl. Akad. Nauk SSSR. – 1963. – V. 150. – P. 764-766; Amati D., Fubini S., Stanghellini A. Theory of high energy scattering and multiple production. // Nuovo Cimento. – 1962. – V. 26. – P.896–954.; Arbuzov B. A. and Rochev V. E. Equation for the imaginary part of the scattering amplitude in the ladder approximation Yad. Fiz. – 1975. – V. 21. – P. 883–889(in Russian);).; Callan Curtis G., Jr. and Goldberger M.L. Model calculations of electroproduction and inclusive annihilation cross sections.// Phys. Rev. D. – 1975.– V.11. – P. 1553–1562.; Gadjiev S. A. and Jafarov R. G. On the Regge asymptotics of the scattering amplitude of scalar particles at arbitrary angles. // Bull. Lebedev Phys. Inst. – 1986 – No. 11 – P. 25-28(in Russian).

for different models of the quantum field theory.

To calculate the asymptotic scattering amplitudes of particular processes at high energies, the method proposed in work

Gadjiev S. A. and Jafarov R. G. On the Regge asymptotics of the scattering amplitude of scalar particles at arbitrary angles. // Bull. Lebedev Phys. Inst. – 1986 – No. 11 – P. 25-28(in Russian).

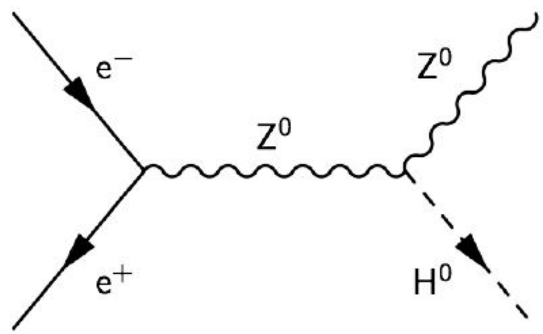
and further developed in work

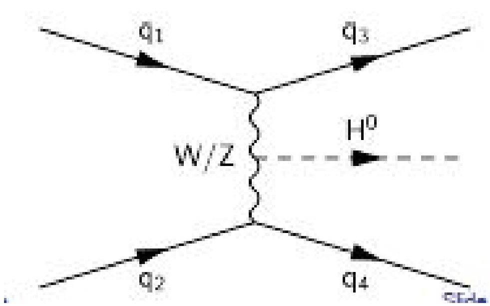
Jafarov R. G. Model Bethe-Salpeter equations for the scattering amplitude of Higgs scalars with solutions. // Russ. Phys. Jour. – 2024. – V. 67. – No 5. – P. 20-26(in Russian).

is convenient from the technical viewpoint.

First of all, it is of methodological interest to study theoretically the processes of scattering of the fermion-antifermion with exchanging of the Higgs bosons and decay of Higgs boson into two massive bosons. For example, the decay into two Z (or W)-bosons bosons according to the ladder Bethe-Salpeter (BS) .

In the present work, we undertake an attempt of calculating fermion-antifermion scattering amplitude with exchanging of the bosons in the ladder approximation in the covariant R_x gauge that can provide the basis for studying the processes of type ee^{+} ® Z^{0*} ® $Z^{0}H^{0}$ and the inclusive channel in $p\overline{p}$ collisions.



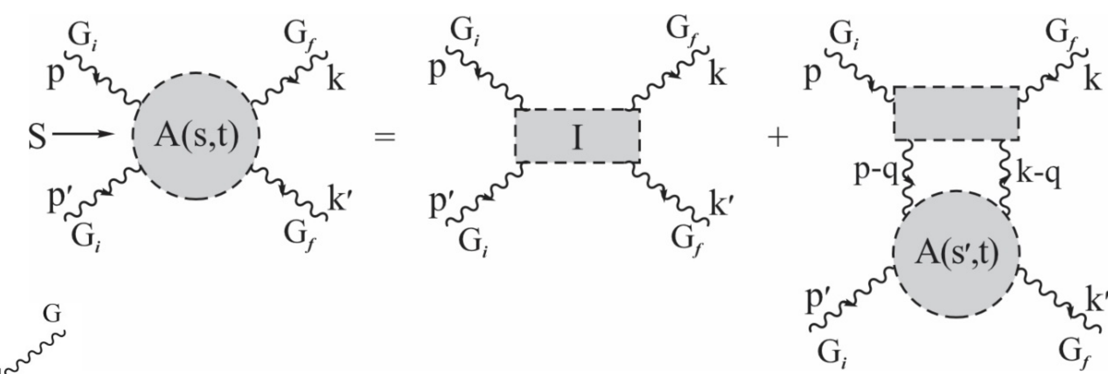


MODEL BETHE-SALPETER type EQUATIONS 14.

Amati-Bertocci-Fubini-Stanghellini-Tonin and Arbuzov-Rochev Equations

In this approximation authors begin treating "electroproduction" but with all particles being treated as scalars. The process is, as usual, virtual photon (q) incident on "nucleon" (p) producing hadrons over which they sums The kinemaqtics are shown in following figure

Fig.1.



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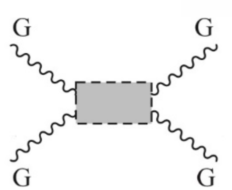

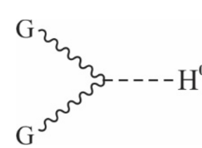

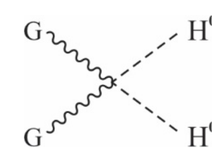

(1) **15.**

this Equation called as Amati-Bertocci-Fubini-Stanghellini-Tonin Equation

and

$$T\left(p,q\right)=B\left(p,q\right)+\frac{1}{\left(2\pi\right)^{k}}\int d^{k}q'K\left(q',q\right)\Delta^{2}\left(q'\right)T\left(p,q'\right) \quad (2)$$

is Arbuzov-Rochev Equation.

Both Group using different approximations for some substructure of integrand as expansions after some calculations received solutions in the form of a power function (up to logarithmic factors) of total energy

$f\left(s,t,m\right)s^{a\left[g,t\right]}$

where $f\left(s,t,m\right)$ some function of total energy s, transfers momentum t and particle masses m. Power function include only coupling constant, mass and t.

In our investigation we use to (1) and (2) hybrid Equation for scattering amplitude in ladder approximation

$$A(p,p',k,k';s,t)=V^{2}\Delta(p+p')+ \tag{3}$$

$$\frac{V^{2}}{(2\pi)^{4}}\int d^{4}q\,\Delta(q)\Delta(p-q)\Delta(k-q)A(q,p',k,k';s',t)$$

where vertex function, which include itself coupling constants

$$g_{HF\bar{F}} \equiv y_F = m_F/\upsilon\,, \qquad g_{HGG} = 2m_G^2/\upsilon\,,$$

$$g_{HHGG} = 2m_G^2/\upsilon^2, \quad g_{HHH} = 3m_H^2/\upsilon\,, \quad g_{HHHH} = 3m_H^2/\upsilon^2\,,$$

$$G = W^{\pm}\left(Z^{0}\right), \qquad \delta_W = 1,\ \delta_{Z^0} = 1/2$$

In our model the hybrid Equation for boson-boson scattering amplitude for imaginary part in the theory with SSB has the form: **17.**

$$F_{G_iG_i\to H\to G_fG_f}\left(p^2, p'^2; s,t\right) = -\pi V_{G_iG_iH}\,\delta\left[\left(p+p'\right)^2 - M_H^2\right] V_{G_fG_fH}$$

$$-\frac{\pi V_{G_iG_iH} V_{G_fG_fH}}{(2\pi)^4}\int dq_0 \left|\vec{q}\right|^2 d\left|\vec{q}\right| \sin\theta\, d\theta\, d\varphi\, ds'\,\delta\left(\left(p+p'-q\right)^2 - s'\right)\theta\left(q_0\right)\delta\left[q^2 - M_H^2\right]\theta\left(q_0+p'_0\right)$$

$$\times\frac{F_{G_iG_i\to H\to G_fG_f}\left(q^2, p'^2; s'\right)}{\left[\left(p-q\right)^2 - M_{G_i}^2\right]\left[\left(p-q\right)^2 - M_{G_f}^2\right]} \qquad \mathbf{(4)}$$

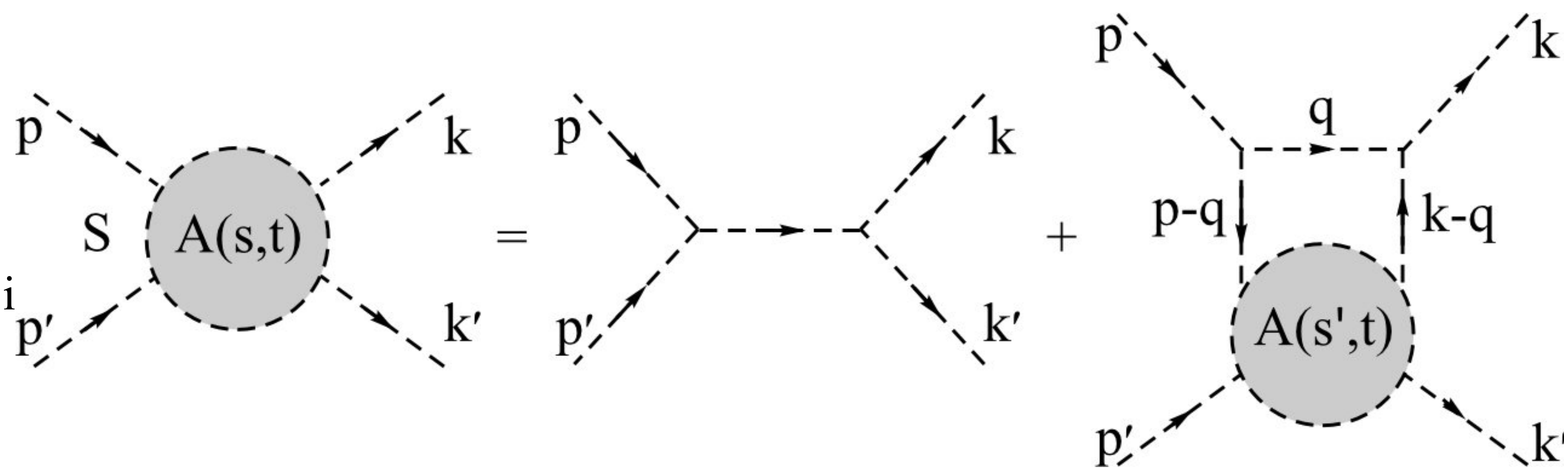

Fig.2. Si

GENERAL EQUATION FOR FERMION-BOSON SCATTERING

The fermion-fermion scattering amplitude in the single-particle ladder approximation of the theory with the three-linear interaction: satisfies the BS type equation

$$\bar{\psi}(p')A_{\alpha\beta}(p,p',k,k')\psi(p') = \bar{\psi}(p')V_{FB_{ex}\bar{F}}\Delta_{B_{ex}}(p+p')V_{BB_{ex}B}\delta_{\alpha\beta}\psi(p') +$$

$$V_{FB_{ex}\bar{F}}V_{BB_{ex}B}\times\int d\tilde{q}\,\bar{\psi}(p')\Delta_{B_{ex}}(q)A_{\alpha\alpha'}(q,p',k,k')\Delta_F(p-q)_{\alpha'\beta}\Delta_B(k-q)\psi(p')$$

where $d\tilde{q} = \frac{d^4 q}{(2\pi)^4}$, p, p' and k, k' are initial and final 4-momenta of fermions and bosons, respectively. The amplitude $A_{\alpha\beta}$ is the function of the following invariants:

$$p^2, p'^2, k^2, k'^2.$$

$$pp' F_1(s,t;p^2) + M_F F_2(s,t;p^2) = -\pi M_F V_{FB_{ex}\bar{F}} V_{BB_{ex}B}\, \delta\left[s - M_{B_{ex}}^2\right] +$$

$$\pi V_{FB_{ex}\bar{F}} V_{BB_{ex}B} \cdot \int d\tilde{q}\, ds' \frac{\delta\left[q^2 - M_{B_{ex}}^2\right]\theta(q_0)\,\delta\left((p+p'-q)^2 - s'\right)\theta(p_0 + p'_0 - q_0)}{\left[p^2 - M_F^2 + q^2 - 2p_0q_0 + 2|\vec{p}||\vec{q}|\cos\theta\right]\left[k^2 - M_{B_f}^2 + q^2 - 2k_0q_0 + 2|\vec{k}||\vec{q}|\cos\theta_1\right]} \times$$

$$\left\{F_1\left(s',t;(p-q)^2,(k-q)^2\right)\left[M_F(p-q)^2 + M_F p'(p-q)\right] + F_2\left(s',t;(p-q)^2,(k-q)^2\right)\left[p'(p-q) + M_F^2\right]\right\}$$

(6)

$$M_F p^2 F_1(s,t;p^2) + pp' F_2(s,t;p^2) = -\pi V_{FB_{ex}\bar{F}} V_{BB_{ex}B}\, \delta\left[s - M_{B_{ex}}^2\right] pp' +$$

$$\pi V_{FB_{ex}\bar{F}} V_{BB_{ex}B} \cdot \int d\tilde{q}\, ds' \frac{\delta\left[q^2 - M_{B_{ex}}^2\right]\theta(q_0)\,\delta\left((p+p'-q)^2 - s'\right)\theta(p_0 + p'_0 - q_0)}{\left[p^2 - M_F^2 + q^2 - 2p_0q_0 + 2|\vec{p}||\vec{q}|\cos\theta\right]\left[k^2 - M_{B_f}^2 + q^2 - 2k_0q_0 + 2|\vec{k}||\vec{q}|\cos\theta_1\right]} \times$$

$$\left\{F_1\left(s',t;(p-q)^2,(k-q)^2\right)\left[pp'(p-q)^2 + M_F^2 \cdot p(p-q)\right] + F_2\left(s',t;(p-q)^2,(k-q)^2\right)\left[M_F \cdot p(p-q) + M_F \cdot pp'\right]\right\}$$

Look for the solutions of Eqs. (6) in the Regge region in the form

$$F_1\left(s,t;p^2\right) \approx c_1 \left(\frac{s'}{m^2}\right)^{\alpha(t)} \frac{1}{p^2}, \quad F_1\left(s,t;p^2\right) \approx c_2 m \left(\frac{s'}{m^2}\right)^{\alpha(t)}$$

where c_1 and c_2 are constants.

Using these functions in (6) and then üe get the particle with momentum k on the mass shell $k^2 = M_B^2$ and the particle with momentum p near the mass shell $p^2 \to M_f^2$, and the correction to the exist for the mass shell in high energies $s \to \infty$ is very small.

$$\left.\begin{aligned} \frac{1}{M_B^2} &= IG\left[\frac{1}{M_B^2}+\frac{c_2}{c_1}\right], \\ \frac{c_2}{c_1}M_B &= IG \end{aligned}\right\},$$

where

$$I=\left(\frac{2}{|\vec{p}|}\right)^2\int_0^s\frac{ds'}{s-s'}\left(\frac{s'}{s}\right)^{\alpha(t)}\left[-\frac{1}{1-\beta^2}+\frac{\varepsilon}{3}\frac{1}{\left(1-\beta^2\right)^2}\right],\qquad \beta=\frac{\sqrt{s}}{2|\vec{p}|}$$

В настоящее время İSAAC GROUP Collaboration **22.** на стадии анализа структуры уравнений и определения аналитических выражений реджевского показателя. Также согласуем гибридное решение системы уравнений в виде степенной и дважды-логифмической асимптотической форме.

В связи напряженной геополитической обстановки в юго-западной части Евроазии, авиапоездки ограничены, также в связи позднего подтверждения моего участия на воркшопе, моя группа с наступлением сезона летних отпусков приостановила работу коллаборации до осени 2025!

Согласования полученных данных с экпериментом планируем доложить на семинара теоротдела Логунов ИФВЭ Протвино в ноябре!

THANK YOU FOR YOUR ATTENTION!

If you have any questions, write to me at the address

r.g.jafarov@gmail.com

I will certainly answer you.